

INVESTIGATION OF LASER DYNAMICS, MODULATION AND CONTROL
BY MEANS OF INTRA-CAVITY TIME VARYING PERTURBATION

under the direction of

S. E. Harris

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INTRODUCTION

The work under this grant is generally concerned with the generation, control, and stabilization of optical frequency radiation. In particular, we are now concerned with attaining tunable optical sources by means of nonlinear optical techniques. During the past half year we have finally attained success in our attempt to develop a tunable visible cw optical parametric oscillator. This work is described in detail in the following section of this report.

Work on the backward wave oscillator project referred to in previous reports has temporarily been suspended, but is expected to commence again in about three to six months.

During this period the following publication has been submitted for publication and is included as an Appendix:

R. L. Byer, M. K. Oshman, J. F. Young, and S. E. Harris, "Visible CW Parametric Oscillator," to be published in Applied Physics Letters.

The following oral disclosure has also been presented:

R. L. Byer, M. K. Oshman, J. F. Young, and S. E. Harris, "CW Parametric Oscillator," Third International Quantum Electronics Conference, Miami, Florida, May 1968.

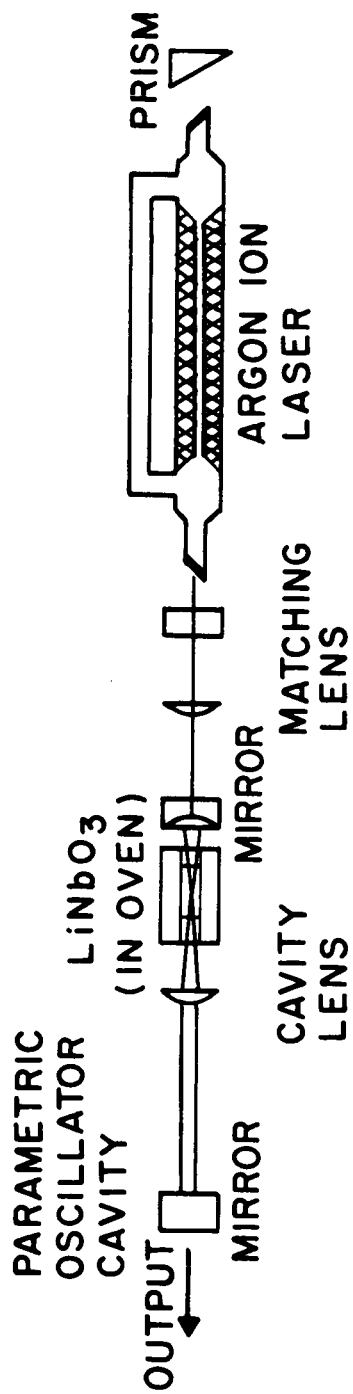
1. Parametric Oscillation at Optical Frequencies (R. L. Byer, J. F. Young, and S. E. Harris)

In the previous report we presented progress made in constructing an argon pumped cw parametric oscillator. We report here the successful operation of a visible, cw, 5145 \AA pumped parametric oscillator. The steps leading to the successful parametric oscillator and the oscillator's operating characteristics will be discussed. Success of the oscillator depended upon the availability of a good crystal of LiNbO_3 . The crystal testing procedure and results reported last time led to the high quality crystal 1.65 cm long, boule #103, which was used in the first oscillator experiment.

Figure 1 shows a schematic of the 5145 \AA argon ion laser pumped parametric oscillator. The cavity mirrors were high quality low loss reflectors coated to be highly reflecting at 2.00μ and 6880 \AA , the idler and signal respectively. The antireflection coating on the crystal and on the quartz lens was similarly centered in wavelengths. The internal lens recollimated the diverging signal and idler beams so that a cavity of the same length as the laser cavity could be used. This allowed the full multimode pump power of the argon laser to be used in driving the parametric oscillator as shown by Harris.¹

The combined losses of the mirrors, crystal, and lens is shown as a function of wavelength in Fig. 2. From this figure we see that the low loss bandwidth over which the oscillator could be tuned is about 300 \AA . When operating, the oscillator was tuned over this region by

¹S. E. Harris, IEEE J. of Quant. Electr. QE-2, 701 (1966).



5145 Å PUMPED PARAMETRIC OSCILLATOR

Figure 1

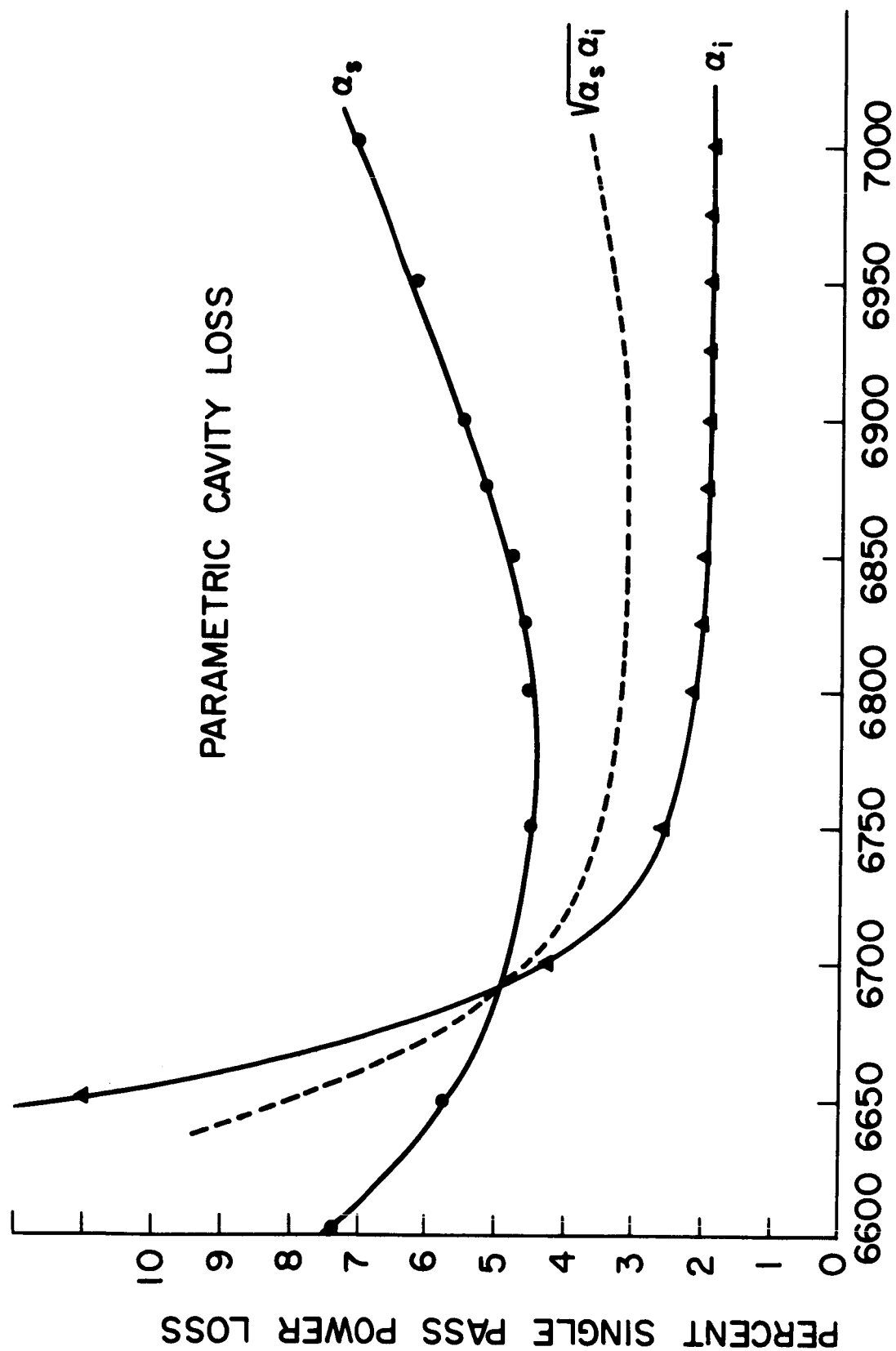


Figure 2

changing the crystal temperature. The 300 \AA tuning range could be scanned in about ten minutes with no loss in oscillator power.

Figure 3 shows the mode sizes in the parametric oscillator cavity as a function of internal lens position. The optimum operating point was for a mode size of 34μ at the signal and 67μ at the idler. This gave a calculated optimum pump mode size of 29μ in the crystal.

The experiment was initially aligned with the aid of a He-Xe laser oscillating at 2.026μ in the infrared. A Spectra-Physics model 115 laser was refilled with He-Xe mixture so that the 2.026μ line would oscillate. This laser was then inserted into the parametric oscillator cavity and made to oscillate by careful alignment of the parametric mirrors. The LiNbO_3 crystal was then temperature tuned so that phase matching occurred for the parametric amplifier situation; signal at 2.026μ mixing with 5145 \AA pump yields a 6896 \AA output in the red. This red output was then monitored with a photomultiplier and improvements were made in its power by systematically adjusting the parametric cavity alignment. Finally, when maximum signal was obtained, the He-Xe laser was removed from the parametric cavity. With a small adjustment of one mirror the oscillator was then above threshold. The He-Xe alignment aid is no longer needed to align the oscillator since experience with the oscillator alignment has enabled us to realign it using other means as an adjustment indicator. The initial parametric oscillator results were reported at the International Quantum Electronics Conference in Miami in May, 1968, a few days after its success.

After the initial measurements, subsequently more refined measurements were made to determine the oscillator bandwidth, efficiency,

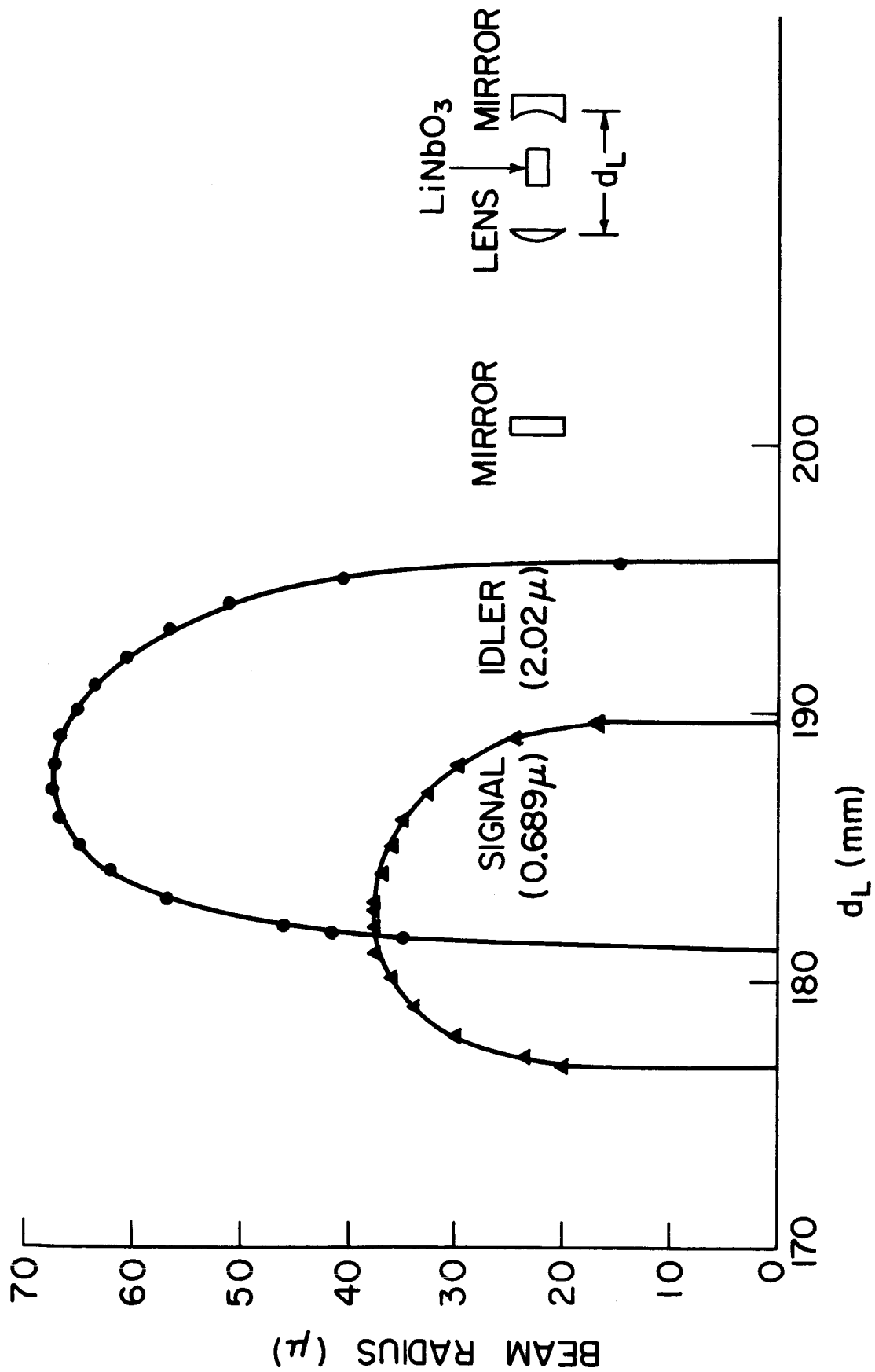


FIGURE 3

temporal behavior, and threshold. These results were reported in a paper recently submitted for publication (Appendix 1).

The measured oscillator threshold was 410 mW. This value agrees well with the theoretical threshold of 530 mW predicted by the results of Boyd and Ashkin.² The single mode power of our argon laser was about 1/10 that needed to reach threshold thus proving that the multimode power was indeed used in pumping the oscillator.

The bandwidth of the oscillator was measured by time averaged photographs with a Fabry-Perot etalon of 1.0 mm spacing. It was found that the total oscillator bandwidth was 3 cm^{-1} at levels reasonably above threshold. This agrees very well with the theoretically predicted bandwidth of $0.886 / bL = 4.0 \text{ cm}^{-1}$ from the parametric fluorescence theory.

Theoretically it was expected that the signal would oscillate in a single cavity mode for a proper spacing of the $c/2L$ distance. By observing the signal beat notes and the spectrum analyzer with a high resolution spherical Fabry-Perot interferometer, this behavior was observed. The signal tended to oscillate in a single cavity mode at a time, although occasionally two or more axial modes would oscillate.

The temporal behavior of the oscillator was investigated with a fast diode detector. It was found that the oscillator tended to oscillate in 0.1 msec irregular pulses. This temporal behavior had been previously observed by Smith³ in his near degenerate parametric oscillator. In our experiment, the spiking could be attributed to general mounting instabilities since no precaution was taken to isolate the laser or parametric

²G. D. Boyd and A. Ashkin, Phys. Rev. 146, 187 (1966).

³R. G. Smith, J. E. Geusic, H. J. Levinstein, J. J. Rubin, S. Singh, and L. G. Van Uitert, Appl. Phys. Letters 12, 308 (1968).

oscillator from the surroundings. It is expected that progress will be made in reaching more stable operation since this instability does not represent any fundamental operating characteristic.

The power output vs $P/P_{\text{threshold}}$ and the oscillator bandwidth vs $P/P_{\text{threshold}}$ is shown in Fig. 4. The power measurements were made with a thermopile with a 1 sec time constant. The power output is therefore a true average power output of the oscillator. As expected, the peak power was found to be from 5-10 times the average power. It is the peak power that will be obtained when the oscillator is finally made to run steadily. It is interesting to note that the oscillator output is easily visible and has the same sparkling appearance as a He-Ne laser beam. Also, since the oscillator was first made to go, it has been run repeatedly with a very high degree of reliability. Since operation is always very close to threshold due to lack of more pump power this reliability was not expected.

In conclusion, this oscillator represents a very important first step in the realization of tunable optical sources. It has demonstrated the validity of the theory and shown that the technique is a feasible method of obtaining tunable sources in the visible and infrared parts of the spectrum.

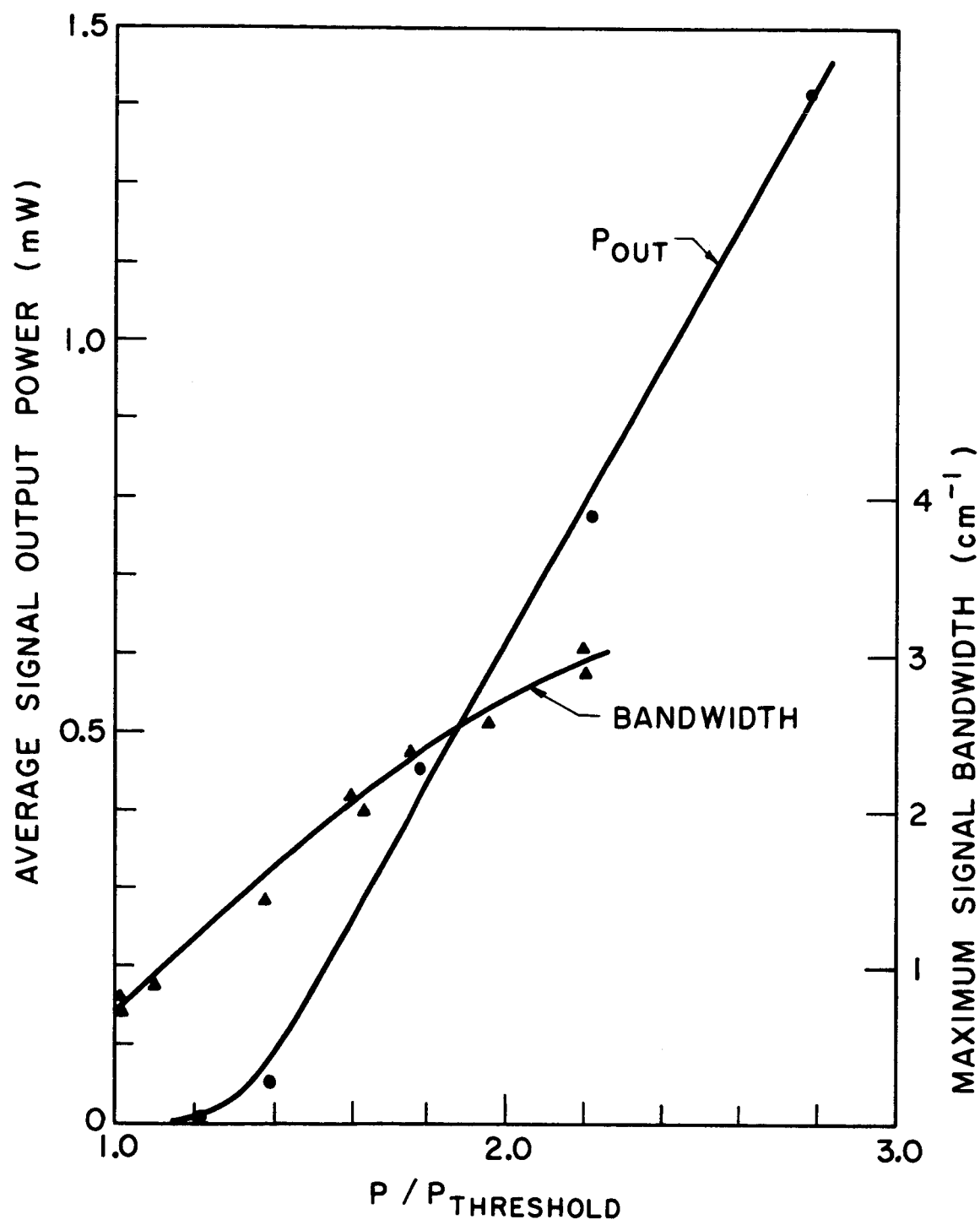


FIGURE 4

APPENDIX 1

"Visible CW Parametric Oscillator"

by

R. L. Byer, M. K. Oshman, J. F. Young, and S. E. Harris

Microwave Laboratory Report No. 1658

July 1968

VISIBLE CW PARAMETRIC OSCILLATOR*

by

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ABSTRACT

A tunable optical parametric oscillator using a 5145 Å argon laser as a pump and lithium niobate as the nonlinear material is reported. The oscillator is constructed in a manner such that the total multi-mode power of the pumping laser is useful for pumping the oscillator. Operation far from degenerate, combined with a relatively long crystal, leads to measured bandwidths of oscillation about ten times less than those previously reported. .

*The work reported in this Letter was sponsored jointly by the National Aeronautics and Space Administration under NASA Grant NGR-05-020-103; and by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under Contract No. F19628-67-C-0038.

[†]M. K. Oshman is presently with Sylvania Electronic Systems, Mountain View, California.

VISIBLE CW PARAMETRIC OSCILLATOR

by

R. L. Byer, M. K. Oshman, J. F. Young, and S. E. Harris

We report the operation of a parametric oscillator using lithium niobate as the nonlinear crystal and the cw output of an argon laser (5145 Å) as the pump. The signal wavelength is tunable from 6800 Å to 7050 Å with the idler in the corresponding range 2.11μ to 1.90μ. Central to the operation of the oscillator is the fact that the full multi-mode power of the laser is useful in pumping the oscillator. In addition, a relatively long crystal operated far from degenerate leads to measured bandwidths of oscillation about ten times less than those previously reported.

Pulsed parametric oscillators have been reported by a number of workers,¹⁻⁴ and a cw-pumped parametric oscillator has recently been reported by Smith, et al.⁵ In contrast to all previous oscillators which used short optical cavities, this oscillator is constructed with a long cavity to allow for the full use of the multi-frequency pump. The separation of the oscillator mirrors is arranged so that the $c/2L$ frequency spacing of the idler modes is equal to the $c/2L$ frequency spacing of the pumping laser. As shown by Harris,⁶ this condition allows the comb of pump modes to cumulatively drive a single signal mode by interacting with the comb of equally spaced idler modes. Although the pump modes may be randomly phased and erratic in amplitude due to competition effects in the laser, corresponding behavior of the idler modes

compensates to allow continuous pumping of a single signal mode.

The LiNbO_3 crystal is 1.65 cm long. Second harmonic generation experiments established that the crystal did not exhibit significant refractive index inhomogeneities. The particular wavelengths of the signal and idler allow phase-matching at elevated temperatures (nominally 240°C for our particular crystal) and thus avoid optically induced refractive index inhomogeneities.⁷ These wavelengths also simplify the fabrication of dual-wavelength mirrors and anti-reflection coatings in that a quarter-wave coating at the idler wavelength is a three-quarter wave coating at the signal wavelength.

The measured single-pass power losses of 5.4% and 2.0% at the signal and idler wavelengths, respectively, are due primarily to scatter and reflection losses at the surfaces of the lens, mirrors, and crystal. The narrowband nature of the anti-reflection coatings limits the tuning range of the signal to approximately 300 Å.

For the spacings shown in Fig. 1, the signal and idler beam waists are located at the center of the crystal with calculated radii of 34μ and 67μ , respectively. The internal collimating lens is necessary to allow a long optical cavity while maintaining small signal and idler spot sizes at the output mirror. The pump was focused to a beam waist of 29μ . For these beam sizes and losses, the results of Boyd and Ashkin⁸ predict a single-mode threshold power of approximately 530 mW.

Realization of theoretical threshold depends critically on cavity alignment. Initial alignment was aided greatly by placing a He-Xe plasma tube into the parametric oscillator cavity. The difference frequency (6896 Å) signal generated between the 2.02μ He-Xe oscillation and the

5145 Å pump was then maximized by adjusting the oscillator components. Removing the plasma tube and performing a final adjustment yielded a threshold power of 410 mW. Observation of the beat spectrum of the laser output verified the erratic, multi-mode nature of the pump which, together with the threshold results, confirms the fact that the full multi-mode power of the laser was useful in pumping the oscillator.

The results of measurements of the output power of the oscillator are shown in Fig. 2. A maximum output power of 1.5 mW as measured with a thermopile was observed when the pumping power was 2.8 times the threshold value. The output mirror of the oscillator has a transmission of only 0.04% and it is expected that larger powers will be obtained with optimum output coupling. The parametric output consists of pulses with lengths typically 0.1 msec long but occasionally lasting 1 msec. The oscillator wavelength can be continuously tuned by changing the temperature of the crystal, and the oscillator maintains nearly constant output during the tuning process.

Measurements of the spectrum of the oscillator were made with a scanning Fabry-Perot etalon. With an etalon spacing of 1.0 mm corresponding to a free spectral range of 5.0 cm^{-1} , it was found that the total oscillation width (i.e., the bandwidth over which individual cavity modes can oscillate) approaches 3 cm^{-1} if the oscillator is driven reasonably far above threshold. For weaker pump drives this bandwidth is reduced, as shown in Fig. 2. The maximum oscillation width of 3 cm^{-1} is in good agreement with the minimum spontaneous emission bandwidth of $0.886/bL = 4.0 \text{ cm}^{-1}$ where

$$b = \frac{\partial k_s}{\partial \nu_s} - \frac{\partial k_i}{\partial \nu_i}$$

and L is the length of the nonlinear crystal.⁹

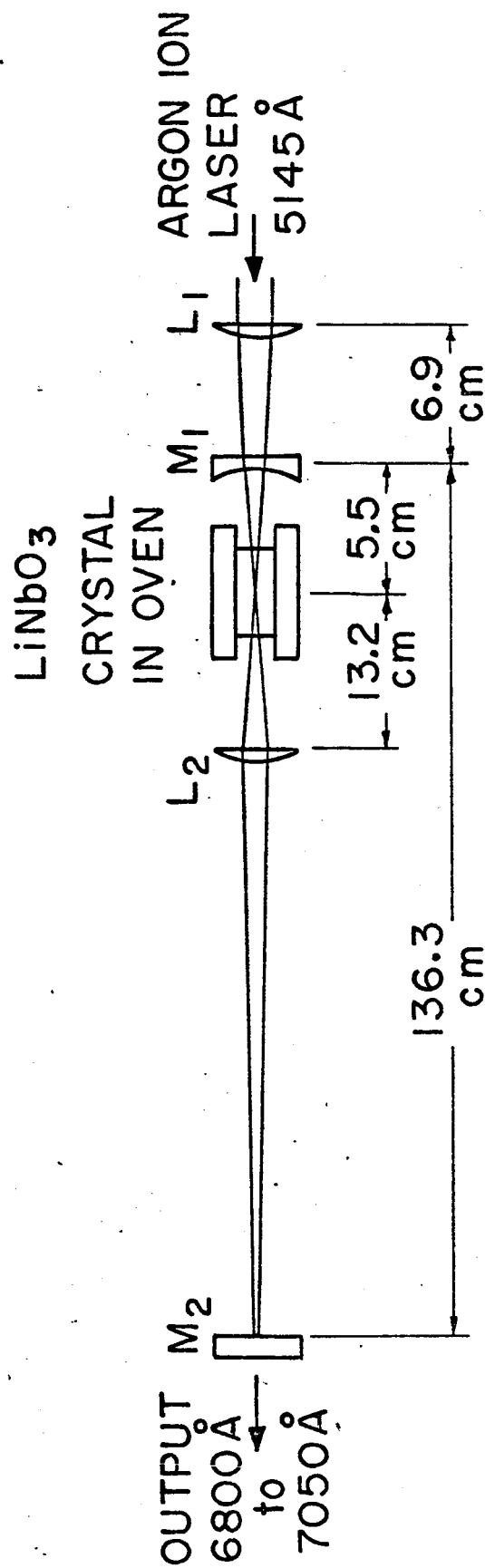
A Spectra-Physics confocal etalon with a free spectral range of about 3 GHz was used to examine the output spectrum in finer detail. The signal tended to oscillate in a single axial mode at a time, although occasionally two or more modes were observed simultaneously. Erratic signal beat notes at $c/2L$, $2c/2L$, and $3c/2L$ were observed on an rf spectrum analyzer.

ACKNOWLEDGEMENTS

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9. R. L. Byer and S. E. Harris, Phys. Rev. 168, 1064 (1968).



M_1 5cm RADIUS MIRROR

M_2 FLAT MIRROR

L_1 MATCHING LENS, FOCAL LENGTH 9.8cm (5145 Å)

L_2 COLLIMATING LENS, FOCAL LENGTH 11.8cm (6900 Å)

FIG. 1--Schematic of parametric oscillator.

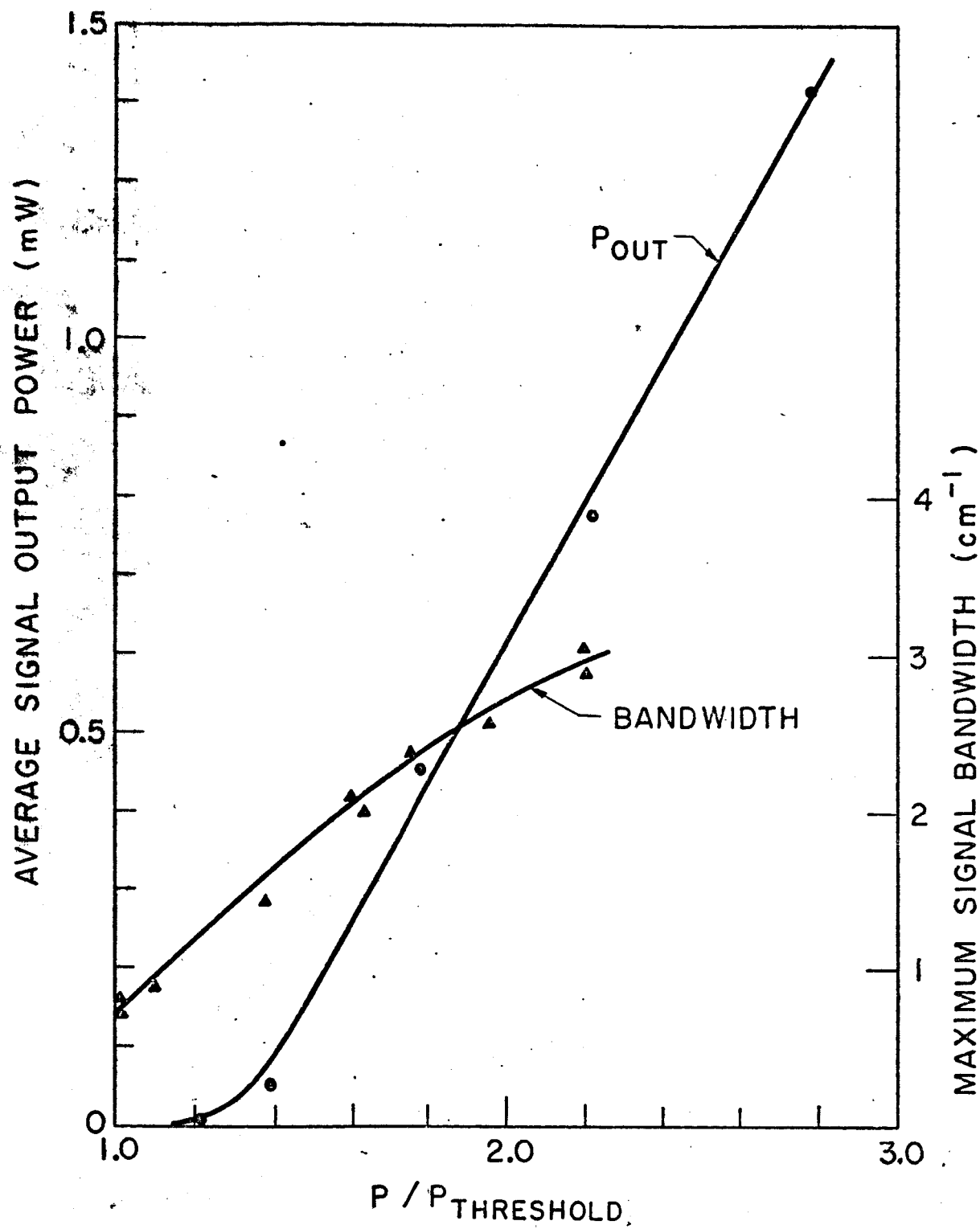


FIG. 2--Power output and bandwidth vs $P_{\text{pump}}/P_{\text{pump}}$ (threshold).